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# Non double couple seismic sources, faults interaction and hypothesis of self-organized criticality

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**Abstract.** Non double couple (NDC) sources are considered in framework of the hypothesis that the process of seismic rupture can be viewed as a result of complicated fault geometry and its segmentation. Analytical approach is found to reveal reliability of NDC measure taking into consideration the values of seismic moment tensor errors. The study focuses on the comparison of the deformation modes of the NDC sources with the stress states in its vicinity. The deformation modes of faulting and fracturing at a small scale in NDC earthquake focus and at regional scale in geological unit were investigated using at the last case summation of seismic moment tensors. These local and regional deformation modes in some of geodynamic regimes confirm the self-similarity assumption. For the whole data set scaling relations seem to be more complicated. This feature implies that besides stresses second order factors, as the hydrothermal or magmatic pore fluids in rock, influence source characteristics and bring new complications in scaling relations.

## 1 Introduction and main approach

The hypothesis that seismicity may be considered as self-organized critical process (SOC) take into consideration multi-scale hierarchical structure of real geological medium and its heterogeneity. In result the SOC approach leads to rather well description of earthquakes statistics (first of all the Gutenberg-Richter law) but up to now it was not so helpful for understanding of individual EQ-triggering process at local scale level.

In this study NDC sources are used to investigate strain variations related to interacting faults and rupture processes at the local scale level. At the NDC foci, a localized stress concentration is expected from numerical models of complex fault along geometrical barriers. Besides that types of active crustal deformation directly reflected by type of NDC seismic sources. With a knowledge of NDC focal mechanisms it would be possible to investigate local deformation modes in lithosphere and upper mantle. If we gain a better understanding of the NDC individual seismic events, these tiny local objects will become a very powerful tool for understanding heterogeneous and non-steady deformation pattern in seismogenic regions.

On a short-term temporal scale we can consider earthquake precursors recorded at the Earth's surface, atmosphere and ionosphere, which are indirect responses of the upper crust to deformation processes in the focus. Geophysical parameters, such as pulsed electromagnetic radiation, electrical resistivity, hydro-geochemical regime, acoustic emission etc., which are best pronounced , are controlled by strain rates in the vicinity of an observation point (Hayakawa and Molchanov, 2002). It is important to clear up the mechanism of link of these processes (Parrot, 2002).

The analysis of deformation process in earthquakes foci makes it possible to get a better insight into various aspects of faulting and earthquakes in real media. Stable isotopic and rare-earth elemental data document the water infiltration, during brittle deformation and alteration of the fault zone. The interaction of fluids with contrasting lithologies led to different alteration processes affecting fault weakening or strengthening. Recognition of the fundamental role of an electrically conducting fluids, such as saline pore water, explains many features of observed data (Hayakawa and Molchanov, 2002). The control of fluid flow by plastic deformation during metamorphism is critical to our understanding of metamorphic processes. Natural fault networks involve a very broad range of fault lengths, modeled in general by a power law length distribution. The basic mechanical process responsible for earthquakes and faulting is not known well enough. Principle of the effective stress coupled to the Coulomb failure criterion introduces mechanical coupling between fault slip and pore fluid pressure.

Various geological observations and field studies demonstrate the consequences of fluid flow control by deformation, so that the concept appears to be accepted, at least for

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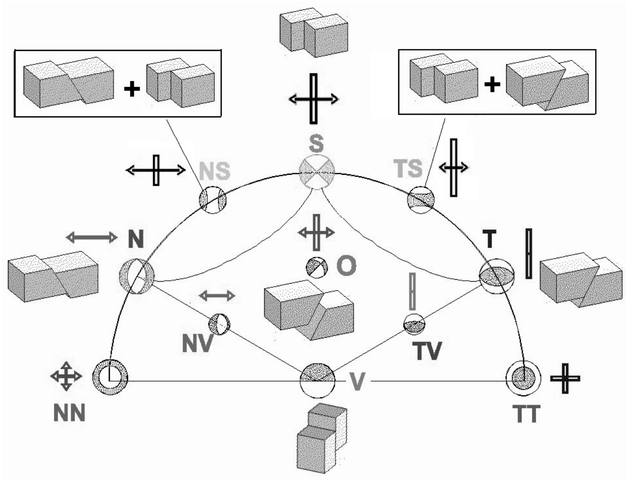


**Fig. 1.** Typical examples of seismic moment tensors in "beach-ball" notation with subdivision into eleven types: 1–11 – characteristic deformation environments: T-thrust environment; S – strike-slip; N – normal; V – vertical fault; NDC-regimes: TS – transpressional; NS – transtensional; NN – two-sided extension; TT – two-sided compression. The compression is shown by a thick solid clip line, the thin line (orthogonal to the first one) shows the orientation of extension. Crustal blocks sliding along each other are shown schematically. The numerical slips lead to NDC-sources.

small-scale faults systems (Ord and Oliver, 1997; Hayakawa and Molchanov, 2002; Yunga et al., 2002). As known, the seismic process depends on distribution of stresses in a volume of rocks. Qualitative analysis of the redistribution of stresses in an elastic medium with scaling organization of faults demonstrate that the inhomogenity of stresses near tips of such fault zones is altered drastically. It has been shown that of great importance are regional variations in the stress state caused by the processes of redistribution of crustal stresses during seismic activity in the region as well as by more distant seismogeodynamic processes on interplate boundaries.

As concerned the interaction mechanisms, the SOC approach implies a possibility of collective (ensemble) interaction. The focal mechanisms in the group of seismic events are controlled by the interaction of stress fields in the region. The use of earthquake focal mechanisms and seismic moment tensors for analysis of seismotectonic deformation is a fundamental part of the up-date geodynamic (Yunga, 1996). The nature of the stress field and style of deformation associated with plate motions mostly is determined from earthquake focal mechanisms (Aki and Richards, 1980).

As such, it has been widely used to evaluate, in a more or less independent manner, the nature of recent crustal deformation on scales ranging from global to regional and local. Tectonic deformation and the other geodynamic manifestations may be viewed as a response of the Earth to the stresses acting in its upper layers and resulting in such phenomena as seismicity and the present relief formed mainly during the neotectonic phase (Yunga, 1996).

Dealing with seismic manifestations, we may identify the seismotectonic deformation component caused by manifold slips in earthquake sources (Molnar, 1983). The relationship between seismic and geodynamic processes is of great importance for understanding the nature plate tectonics. On the other hand, current seismological observations confirm that the pattern of seismic waves from some earthquakes cannot be produced by slip along a planar fault surface. Several recent studies have revealed non-double-couple components (NDC) in catalogs of seismic moment tensors (Randall, 1971; Kuge and Lay, 1994; Frohlich, 1994, 1995; Nettles and Ekstrom, 1998; Zhang, 1998; Vavrycuk, 2002). Physical mechanism is required to explain the observed varieties of these NDC earthquakes. The most common explanation is that these earthquakes are complex, with stress released on several nonparallel fault surfaces (Fig. 1), (e.g. Kuge and Lay, 1994; Frohlich, 1994, 1995).

We demonstrate qualitatively that study of NDC sources provides a context for understanding how earthquakes may be triggered by superposition transients and internal stresses. We observe a characteristic style of deformation involving a set of NDC events. We assume that NDC earthquake mechanisms is a complex deformation process and test two hypotheses about the effect of superposition transients and internal stresses.

Our first hypothesis is that transient loads transient stresses associated with plate motions lead to uniform stress state; i.e. scale independent stress state would have happened due to constant background loading alone. These simple "stress-uniform" models predict geometrical kinematic relationships between the fault offsets and the transient characteristics of stresses. In this case, we need to assume a homogeneous stress field, independence between faults, and parallelism between shear stress and slip vector on the sliding plane. A uniform style of deformation occurs in a test subregion if majority of the NDC events are associated with the same type of deformation.

Our second hypothesis is that essentially inhomogeneous stress state triggered NDC earthquakes that would not have happened without the superposition of transient and internal load (i.e. accumulated strain energy would have been revived via other mechanisms such as hydro-metamorhic reactions). We test this using statistical distribution of types of deformation in NDC foci which directly reflect the deformation modes.

Calculations are made to distinguish between two alternative hypotheses concerning the style of deformation of lithosphere in specific NDC test regions over the world.

## 2 Analytical approach and evaluation of NDC significance

Analytical approach is found to reveal reliability of NDC measure taking into account the values of seismic moment tensor errors. Let us consider the determinant Det ($\mathbf{M}_{ij}$) which is composed from elements of seismic moment tensor matrix $\mathbf{M}_{ij}$. When the focal mechanism is double couple we have Det ($\mathbf{M}_{ij}$)=0. But if we take into account the errors ($\Delta\mathbf{M}_{ij}$) of seismic moment matrix elements $\mathbf{M}_{ij}$ we have to consider all possible variations of Det ($\mathbf{M}_{ij}$) when $\mathbf{M}_{ij}$ arbitrary changes within a segment ($\mathbf{M}_{ij}-\Delta\mathbf{M}_{ij}$, $\mathbf{M}_{ij}+\Delta\mathbf{M}_{ij}$). It can be shown, using the enough condition of existing a local extreme of function Det ($\mathbf{M}_{ij}$), that function of 6 variables Det ($\mathbf{M}_{ij}$) hasn't any local extremes within the interval ($\mathbf{M}_{ij}-\Delta\mathbf{M}_{ij}$, $\mathbf{M}_{ij}+\Delta\mathbf{M}_{ij}$). Thus one can conclude that Det ($\mathbf{M}_{ij}$) achieves its extreme values in the ends of the segment ($\mathbf{M}_{ij}-\Delta\mathbf{M}_{ij}$, $\mathbf{M}_{ij}+\Delta\mathbf{M}_{ij}$). So taking into account possible variations of Det ($\mathbf{M}_{ij}$) it is possible to consider only 64 cases instead, for example, of applying Monte-Carlo method. It must be marked that direct application of Monte-Carlo method with appropriate accuracy in this case leads to consideration about $10^7$ variants of Det ($\mathbf{M}_{ij}$) calculation for each earthquake and would be too much times consumed.

## 3 Data used

The Harvard centroid moment tensor (CMT) catalog has been analyzed to study NDC sources for the time period from 1996 up to March 2004. The CMT catalog includes origin times, hypocentral coordinates and magnitudes mb and MS, taken from the PDE or ISC worldwide catalogs, seismic moment centroid times and locations as well as estimates of seismic moment tensor components (Dziewonski et al., 1981). The CMT catalog entries provide thorough and detailed description of earthquakes, including errors in seismic moment tensor components. The seismic moment tensor uncertainties are especially targeted. First of all our quantitative study of the CMT catalog address the problem of catalog accuracy and its influence on obtained results. Our approach give us possibility to distinguish in a routinely determined solutions artifact and real NDC component. In rather many cases the large non-DC component were just connected with a poor moment tensor solution. Naturally, such earthquakes have been excluded. Our aim has been to compile the CMT subcatalog which exhibit real NDC component for the whole range of seismic moment tensor uncertainties.

## 4 Local scale of seismotectonic deformation

On the local scale level one may investigate stress state and deformation process using CMT-solutions, especially NDC earthquakes. Non double couple sources are usually considered in framework of the hypothesis that the process of seismic rupture can be viewed as a result of complicated fault geometry and its segmentation.

Coefficient Lode-Nadai $\mu_{\mathrm{CMT}}$ was used for the specification of NDC-measure, $\mu_{\mathrm{CMT}}=3*\mathbf{M}_2/(\mathbf{M}_1-\mathbf{M}_3)$, where $\mathbf{M}_1$, $\mathbf{M}_2$, $\mathbf{M}_3$ are principal values of seismic moment tensor $\mathbf{M}_{ij}$ ($\mathbf{M}_1\geq\mathbf{M}_2\geq\mathbf{M}_3$), (abs ($\mu_{\mathrm{CMT}}$)$\leq$1). This parameter is of special interest as it describe local deformation mode in earthquake source.

There is observational evidence that at least in declared CMT uncertaintences many of earthquakes are non-double couple events.

The CMT subcatalog with 2789 events in the magnitude range $Ms\geq5$ which exhibit real NDC component with abs ($\mu_{\mathrm{CMT}}\geq0.2$ for the whole range of seismic moment tensor uncertainties was compiled and studied. We specially investigated the NDC neighborhoods of each hypocenter of NDC earthquakes.

The circle area of 1.5° radius was studied in each considered NDC case. Then we investigated signs of Lode-Nadai coefficient for all of NDC events in limits of area. We choosed only statistically significant cases with not less then 7 NDC events in the vicinity of major NDC earthquake (EQ). The sign test at 95% level of significance was used thus. It was found that in vicinities of 90 NDC earthquakes there was not less then 7 NDC events. In 24 cases the sign of $\mu_{\mathrm{CMT}}$ major EQ statistically coincided with the sign of $\mu_{\mathrm{CMT}}$ of neighborhoods events. In 9 cases we have statistically significant negative result. In other 59 cases the mixed signes of NDC events were revealed but as a rule type of main NDC EQ and types of adjacent NDC events are coincided.

## 5 Regional scale of seismotectonic deformation

The next and also important step was examination of NDC earthquakes, revealing their deformation mode in different regions, and especially fixing above mentioned 24 regions with the same type of NDC, and then compare it with regional pattern of seismotectonic deformation (STD).

One of the traditional problems dealt with in geodynamic through focal mechanism solutions, typically for zones of major strike-slip faults, is to reveal the active part of a deep fault responsible for movement (slip) caused by a large earthquake. Another possibility is based on generalization focal mechanisms in framework of seismotectonic deformation, when specific features of the regional deformation field can be analyzed. Note that analysis of all presently available statistics of focal mechanisms of the world provides a comprehensive seismotectonic deformation pattern. Currently, most authors relate geodynamic features with horizontal movements of lithospheric plates. Since spreading is known to be compensated mainly by subduction, the role of the stress state within the lithospheric plates needs to be additionally clarified in both global, regional and local aspects.

The present study focuses on the comparison of the deformation modes of the NDC sources with the states of stresses in its vicinity. The states of stresses are revealed using as a first approximation summation of seismic moment tensors. Stress state or deformation mode is also described by Lode-Nadai coefficient which correspond to principal values of characteristic equation of considered tensor.

For the purpose of regional analysis above mentioned 24 geodynanamic zones were selected which exhibit homogeneity in NDC modes.

**Table 1.** Specially selected and investigated NDC earthquakes parameters, coefficient Lode-Nadai $\mu_{STD}$ gives type of STD in 1.5° vicinity; $\mu_{CMT}$ is NDC measure of CMT, $\Sigma$ is the result of comparison $\mu_{STD}$ with $\mu_{CMT}$ ("y" means yes if coincided, "n" means no, if not consided; "–" is undetermined cases), $\Delta_{CMT}$ is the mean square relative error of normilized CMT, $N_{NDC-total}$ is the total number of NDC events in the vicinity of main earthquake, $N_{NDC-samesignes}$ is the number of NDC events with the same as for main EQ determinant signes in the vicinity of main earthquake.

| Year | Month | Day | M | φ | λ | H | Region | $\mu_{STD}$ | Σ | $\mu_{CMT}$ | $\Delta_{CMT}$ | $N_{NDC}$ total | $N_{NDC,}$ same signes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 76 | 05 | 05 | 6.8 | -29.93 | -177.84 | 35 | KERMADEC ISLANDS | .00 | - | .2 | .0 | 49 | 43 |
| 77 | 05 | 30 | 6.0 | 52.43 | -169.71 | 33 | FOX ISLANDS, ALEUTIANS | -.03 | - | .2 | .1 | 14 | 13 |
| 77 | 11 | 18 | 5.9 | -4.35 | 102.02 | 33 | SOUTHERN SUMATERA | -.05 | - | .2 | .1 | 15 | 12 |
| 81 | 07 | 06 | 7.0 | -22.26 | 171.73 | 33 | LOYALTY ISLANDS REGION | .12 | n | -.4 | .0 19 | 16 | |
| 82 | 09 | 28 | 6.1 | -24.17 | -176.75 | 40 | SOUTH OF FIJI ISLANDS | -.07 | n | .5 | .0 | 15 | 12 |
| 83 | 03 | 23 | 6.2 | -6.62 | 154.61 | 41 | SOLOMON ISLANDS | . 07 | y | .3 | .1 | 19 | 17 |
| 84 | 04 | 06 | 6.0 | -55.49 | 147.06 | 10 | WEST OF MACQUARIE ISLAND | -.02 | - | -.2 | .1 | 10 | 10 |
| 84 | 07 | 16 | 5.9 | -55.26 | -129.47 | 10 | SOUTH PACIFIC CORDILLERA | -.05 | - | -.3 | .1 | 8 | 8 |
| 84 | 12 | 30 | 6.9 | -36.73 | 177.50 | 33 | OFF E CST NORTH IS.,N.Z. | -.56 | y | -.2 | .1 | 9 | 9 |
| 85 | 09 | 26 | 6.9 | -34.63 | -178.69 | 33 | SOUTH OF KERMADEC IS. | -.05 | - | .4 | .0 | 18 | 14 |
| 87 | 02 | 06 | 6.0 | 36.88 | 141.71 | 36 | NR E COAST HONSHU, JAPAN | .06 | y | .2 | .1 | 16 | 15 |
| 87 | 09 | 27 | 6.6 | 10.76 | -86.40 | 33 | OFF COAST OF COSTA RICA | .04 | - | .3 | .2 | 8 | 8 |
| 90 | 08 | 05 | 6.0 | 36.30 | 141.08 | 42 | NR E COAST HONSHU, JAPAN | .01 | - | .5 | .1 | 18 | 17 |
| 91 | 02 | 16 | 5.7 | 48.22 | 154.37 | 44 | KURIL ISLANDS | -.03 | - | .4 | .1 | 9 | 8 |
| 91 | 03 | 03 | 6.1 | -21.83 | -175.18 | 43 | TONGA ISLANDS | -.01 | - | .2 | .1 | 34 | 24 |
| 92 | 05 | 29 | 5.7 | 31.22 | 141.75 | 19 | SOUTH OF HONSHU, JAPAN | .08 | y | .2 | .1 | 15 | 12 |
| 93 | 06 | 18 | 6.7 | -28.54 | -176.85 | 20 | KERMADEC ISLANDS REGION | -.05 | - | .2 | .0 | 46 | 35 |
| 95 | 04 | 01 | 5.6 | 52.28 | 159.13 | 47 | OFF EAST COAST OF KAMCHATKA | .03 | - | .3 | .0 | 17 | 13 |
| 95 | 06 | 27 | 6.3 | -17.23 | 66.83 | 10 | MASCARENE ISLANDS REGION | -.03 | - | -.4 | .1 | 7 | 7 |
| 95 | 09 | 17 | 6.3 | -17.25 | 66.63 | 10 | MASCARENE ISLANDS REGION | -.01 | - | -.3 | .0 | 7 | 7 |
| 95 | 11 | 24 | 6.3 | 44.54 | 149.09 | 33 | KURIL ISLANDS | .10 | y | .2 | .0 | 29 | 24 |
| 96 | 01 | 30 | 6.7 | -32.83 | -178.27 | 33 | SOUTH OF KERMADEC ISLAND | .06 | y | .2 | .0 | 43 | 36 |
| 97 | 12 | 05 | 6.5 | 53.75 | 161.75 | 33 | OFF EAST COAST OF KAMCHATKA | -.06 | n | .3 | .1 | 15 | 13 |
| 99 | 12 | 10 | 6.2 | -36.21 | -97.32 | 10 | WEST CHILE RISE | -.01 | - | -.2 | .0 | 9 | 9 |

Using the results of this analysis, we test the validity of the self-similarity assumption. In most cases these assumption meet positive answer, marked as "yes". Only in one case answer was definitely "no". In six cases deformation modes were poorly resolved and cannot be used to distinguish local and regional deformation regimes.

As a result of testing first hypothesis we may conclude that among more than 24 investigated geodynamic zones we could find six which are definitely uniform on the NDC deformation mode. Three cases gives ununiform deformation modes, i.e. NDC and STD modes were different. Other 15 cases could not be resolved. The results are summarized in the Table 1.

Thus hypothesis of uniform stress state was confirmed in more cases then opposite one. Nevertheless our result partly support also the second testing hypothesis that expressed in terms of inhomogeneties in stresses. Rather large part of the considered set of NDC events have in its vicinity mixed NDC modes. That is may be considered as the additional evidence of faults interaction and inhomogenity of deformation mode as whole. This feature implies that not only stresses but other factors, as the hydrothermal or magmatic pore fluids in rock, influence source characteristics and bring new complications in scaling relations.

## 6 Discussion

The model described in the present paper belongs to the class of simplified, deterministic models. A fault zone activated during NDC-event is treated as a complex system. The specific mechanisms underlying NDC are not always clear. However, the nonlinear fault interaction with simultaneous offsets result in the non-double couple seismic model which probably cannot be studied quantitatively in more details. We cannot fully clarify the complex nature of physical, chemical, mechanical processes at and near to the tips of a propagating fluid-filled fractures especially in the case of their simultaneous activation. For example, the obvious considerations is that in accordance to theoretical expectations the complex seismic events occurred mainly in the regions of stress concentrations in this overcomplicated process, Thus, the complex micro-structure may course the stress intensity in the process zone to increase too much, so that the uniform regional plate tectonic stress field has not a significant influence.

Nevertheless the last consideration could not be considered as the only. The self-organized criticality (SOC) phenomenon has drawn much attention in connection with the seismic process (Turcotte, 1997, 1999). A system is in a state of self-organized criticality if, when perturbed, it returns to a state of marginal stability that exhibits scale invariance. The system oscillates about a state of marginal stability with a series of slip events in much the same way that it is applied to "avalanches". As it is known power-law (fractal) statistics were obtained for slip events in seismicity that exhibits self-similar behavior through Guttenberg-Richter frequency-magnitude statistics.

We suggest that observed NDC events should be studied in terms of SOC methodology. Indeed, in the terms of SOC these NDC events treated as non-steady deformation may be taken as examples of chaotic flows in nature.

This analogy is partly motivated by the forest-fire model. In this model, an array of boxes is considered and when a box accumulates critical number of events, redistribution involves nearest-neighbor boxes which can lead to further instabilities. In the analogy to the forest-fire model we argue that the process of simultaneous offsets dominates in the non-double couple model.

We can further extend outlined above model and suggest that faults play a role similar to role played by slider blocks in the SOC model of seismicity. A wide variety of slider-block models can exhibit classic chaotic behavior as these have been reviewed by Turcotte (1999). In these models, the slip of one fault plane could lead to the instability of either or both of the adjacent blocks, which would then be allowed to slip in a subsequent step or steps, until all blocks were again stable. As the redistribution involves only nearest neighbor blocks, it is a cellular-automata model. Redistribution can lead to further instabilities with the possibility of an 'avalanche' of slip events.

Thus NDC event related with simultaneous complex faulting may be treated in terms of SOC as seismic "avalanche". Self-organized criticality may be realized only if the heterogeneity is high enough (Shnirman, Blanter, 1999). To some extent, notions of heterogeneity and chaotization seem to be closely linked. The case then probability of simultaneous slidings of all faults in cluster becomes very high is a classic example of critical point behavior typical for percolation model, forest-fire model, multiplicative cascade model and other models that exhibit self-organized critical behavior. The critical point is reached when a cluster is fulfilled and activated.

## 7 Conclusions

The CMT subcatalog which exhibit real NDC component for the whole range of seismic moment tensor uncertainties was compiled and investigated. There is observational evidence that at least some earthquakes are non-double couple events. This feature is important in fracturing and earthquake sources-forming mechanisms involved in seismic faulting processes. We suggest that NDC events may be considered in terms of the self-organized criticality and methodology of deterministic chaos in seismogenic process. The study of NDC sources provides also a context for understanding how earthquakes may be triggered by superposition transients and internal stresses. The majority of the NDC events have in its vicinity uniform NDC modes, but rather large part of NDC set is characterized as mixed and ununiform. That is may be considered as the evidence of inhomogeneity of deformation mode as whole. This feature implies that such factors, as the hydrothermal or magmatic pore fluids in rock, influence source characteristics and bring new complications in scaling relations.

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